Effect of Berry Size and Sodium Hydroxide Pretreatment on the Drying Characteristics of Blueberries under Infrared Radiation Heating

J. Shi, Z. Pan, T.H. McHugh, D. Wood, Y. Zhu, R.J. Avena-Bustillos, and E. Hirschberg

ABSTRACT: This research studied the effect of berry size and dipping pretreatment in hot sodium hydroxide (NaOH) solution on the drying characteristics of blueberries under infrared radiation (IR) heating. Changes in the microstructure and diffusion coefficient of the berries after the NaOH pretreatment were also determined using scanning electronic microscopy and dynamic vapor sorption (DVS), respectively. To quantify the effect of berry size, nonpretreated bulk blueberries were sorted into 6 groups based on their diameters and dried at 70 °C. To determine the effectiveness of NaOH pretreatment in improving drying characteristics, bulk blueberries of different sizes, both nonpretreated and NaOH pretreated, were dried at constant temperatures of 80 and 90 °C, and variable temperatures of 70 °C for 50 min followed by 90 °C for 50 min. The NaOH pretreatment dipped blueberries in 0.1% NaOH solution with fruit to solution ratio 1:1 (w/v) at initial temperature of 93 °C for 5 s. Results showed that the drying rate increased with decreased berry size. Average moisture diffusivity was in the range of 5.89 to 8.13 m^2/s at 70 °C. The NaOH pretreatment increased drying rate and moisture diffusivity and reduced the number of broken berries, especially at high drying temperatures. Results from SEM observation and DVS showed that the increase in diffusivity coefficients of berry coat and loss of intact microstructure in coat and tissue cells might contribute to the effect of NaOH pretreatment on the IR drying of blueberries.

Keywords: blueberry, diffusivity, infrared drying, pretreatment, size, sodium hydroxide

Introduction

Blueberries (*Vaccinium corymbosum*) are widely consumed because of their flavor and high nutritional value. However, their short shelf life limits market availability and consumption. Osmotic dehydration is a widely used method for drying blueberries to lower product water activity and extend shelf life. For producing dried powder products with high rehydration ability and low sugar content, other drying methods should be used without adding infusion agents (Mowry and Heldman 1974; Rohrbach 1977; Donahue and others 1999). Infrared radiation (IR) is an emerging method that may be used to replace hot air in drying of fruits and vegetables. Compared with hot air drying, IR heating offers many advantages, such as greater energy efficiency, heat transfer rate, and heat flux, which result in higher drying rate and reduced drying time. It has been investigated as a potential method for increasing heating efficiency and obtaining high quality of dried foodstuffs including rice, yams, onions, apples, peaches, herbs, sweet potatoes, and carrots (Abe and Afzal 1997; Hashimoto and Kameoka 1999; Paakkonen and others 1999; Adonis and Khan 2004; Lin and others 2004, 2007; Sharma and others 2005; Wang and Sheng 2006). Although research has been done on using hot air for drying noninfused blueberries and sugar-infused blueberries, there is no reported information available about using IR for drying fresh blueberries (Venkatachalapathy and Raghavan 1998; Chen and others 2001; MacGregor 2005). We recently studied the efficacy of IR drying of sugar infused blueberries and found that IR drying significantly reduced drying time and produced high-quality products (Shi and others 2008). However, it was also observed that the noninfused blueberries had a high percentage of broken berries under high drying temperature. Because of consumer concerns about sugar in infused fruits, there is increased need to study alternative drying methods for producing high-quality, shelf-stable, and nonsugar infused blueberries. Therefore, it is important to study the mass transfer mechanism of nonsugar infused blueberries under IR drying for producing high-quality product.

Blueberries vary in size over a wide range, which could directly affect drying characteristics such as drying rate and moisture diffusivity. For a given variety, sizes may depend on ripeness and sugar content, which is also related to the texture and properties of the fruits. The sizes of blueberries may affect the mass transfer during drying and shrink differently, resulting in different moisture diffusivities and drying rates. MacGregor (2005) studied the effect of berry diameter on the drying characteristics of wild blueberries under convectional air drying. He found that under similar drying conditions, it took longer to reach the final moisture content for larger blueberries than smaller ones, but that the larger berries had a higher mass-losing rate than the smaller ones. Kumar and Tiwari (2006) reported that shape and size also affected the convective mass-transfer coefficient during greenhouse drying. The effect of fruit size on drying characteristics under IR has not been well studied, and this information is essential in designing and operating IR dryers for achieving high-quality product.

MS 20070894 Submitted 12/2/2007, Accepted 4/27/2008. *Author Shi is with College of Food Science and Engineering, Northwest Agricultural and Forestry Univ., 28 Xinong Rd., Yangling, Shaanxi 712100, China. Authors Shi, Pan, McHugh, and Avena-Bustillos are with Processed Foods Research Unit, USDA-ARS-WRRC and author Wood is with Bioproduct Chemistry and Engineering Research Unit, USDA-ARS-WRRC, 800 Buchanan St., Albany, CA 94710, U.S.A. Authors Pan, Zhu, and Avena-Bustillos are with Dept. of Biological and Agricultural Engineering, Univ. of California, Davis, One Shields Ave., Davis, CA 95616, U.S.A. Author Hirschberg is with Innovative Foods Inc., 175 South Spruce St., South San Francisco, CA 94080, U.S.A. Direct inquiries to author Pan (E-mail: zpan@pw.usda.gov).*

doi: 10.1111/j.1750-3841.2008.00816.x

For drying fruits and vegetables, a high drying rate is normally desirable. High temperature may shorten required drying time, but it could cause the berries to rupture and lose juice, especially when temperature is higher than 77 °C (Ramaswamy and Nsonzi 1998; MacGregor 2005; Doymaz 2006). The rupture of fruits during continuous drying at high temperature was thought to be caused by the high vapor pressure under the fruit coat, which in turn was due to the waxy layer outside blueberries inhibiting the water transfer through the fruit coat. It has also been reported that the vapor pressure increased more quickly at higher temperatures than at lower temperatures (George and others 2004). For convectional drying, dipping fruits in hot lye (NaOH) solution for a few seconds significantly improved drying rates and reduced rupture rates of grapes, plums, and blueberries; the supposed reason was the change of microstructure of the berry coat, resulting in increased moisture diffusivity and reduced water vapor pressure (Bolin and others 1975; Raouzeos and Saravacos 1986; Riva and Peri 1986; Doymaz and Pala 2002; Doymaz 2004, 2006; Sacilika and others 2006).

Some pretreatments, including blanching and freezing, can also change the appearance and microstructure of tissue cells (Sapers and others 1984; Allan-Wojtas and others 1999). Information on the structure of tissue cells in blueberries under lye solution pretreatment has not been found. Scanning electric microscopy (SEM) is a widely used method for determining the microstructure of plant tissue and cells, and was used in this study.

Dynamic vapor sorption (DVS) is a new technique developed to collect continuous weight-change data over time at any desired relative humidity (RH) between 0% and 98% in a short amount of time. From the collected moisture-time data, the diffusion coefficient of the tested material can be calculated. This method has been used to test the diffusion coefficient of many kinds of films and solutions (Kim and others 2003; LaTonya and Thomas 2006). In this study, it was used to measure the moisture diffusion properties of the blueberry coat with and without NaOH pretreatment. Knowledge of the moisture diffusion coefficient of the coat could provide fundamental information on the time scale for understanding a drying process.

The objectives of this research were (1) to study the effect of blueberry size and NaOH pretreatment on drying characteristics of blueberries under IR heating, and (2) to discover the intrinsic reason for the influence of hot sodium hydroxide solution by investigating microstructure and moisture diffusion properties of blueberry coat.

Materials and Methods

Blueberries

Blueberries with initial moisture content (*MC*) of 85% (w.b.) were obtained from a local grocery store (Davis, Calif., U.S.A.) and stored in a refrigerator at 4 °C before IR drying. The diameter of the berries was measured with a digital caliper (IP54, Guilin Guanglu Measuring Instrument Co. Ltd., Guilin, China). Berries were sorted into 8 groups based on diameter (± 0.5 mm) with average diameters of less than 10.5, 11, 12, 13, 14, 15, and 16 mm and greater than 16.5 mm. The reported size distribution values are the average of 10 batches with about 100 berries each. Because the percentage of berries with size less than 10.5 mm and greater than 16.5 mm (Figure 1) was very low, the 2 groups were not used in the drying tests.

NaOH pretreatment

An unsorted 200 g blueberry sample (bulk) was dipped for 5 s in 200 mL 0.1% NaOH solution with an initial temperature of 93 °C. The temperature of the solution decreased to 75 °C during the dipping treatment. After the treatment, the berries were removed immediately and quickly rinsed with running tap water for 30 s to wash out the residue of lye solution on the berry surface and to cool them at the same time. The rinsed blueberries were dried with paper towels to get rid of excessive water before IR drying.

IR dryer setup

The catalytic infrared (CIR) dryer used in this study consisted of 2 emitters (Catalytic Drying Technologies LLC., Independence, Kans., U.S.A.), each of which was attached to a stainless steel waveguide (65.5 × 37 × 44 cm) to improve the uniformity of radiation distribution (Figure 2). The blueberries were placed on a metal-screen drying tray (65.5 × 37 cm), which was 47 cm from the upper emitter and 55 cm from the lower emitter. With this setup, the average IR intensities, measured by an Ophir FL205A Thermal Excimer Absorber Head (Ophir Optronics Inc., Wilmington, Mass., U.S.A.), was 4000 W/m^2 for both top and bottom emitters. During drying tests, the temperature of the berries was controlled by adjusting the natural gas input through a valve controlled by an automatic data acquisition system. A type-T thermocouple (Omega Engineering Inc., Stamford, Conn., U.S.A.) with 0.15-s response time was placed underneath the coat of a blueberry. A more detailed

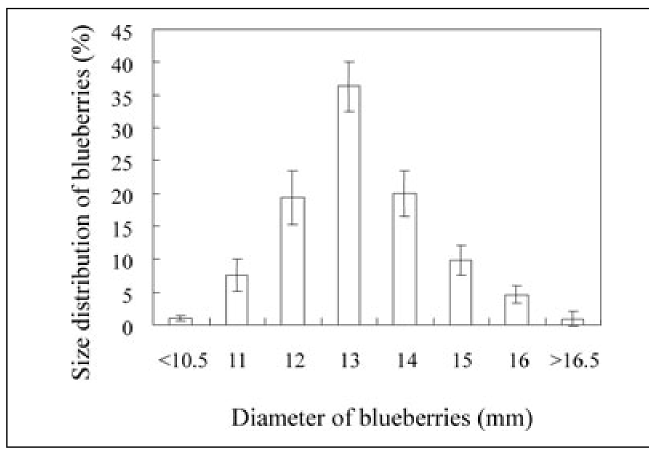

Figure 1 — Size distribution of blueberries.

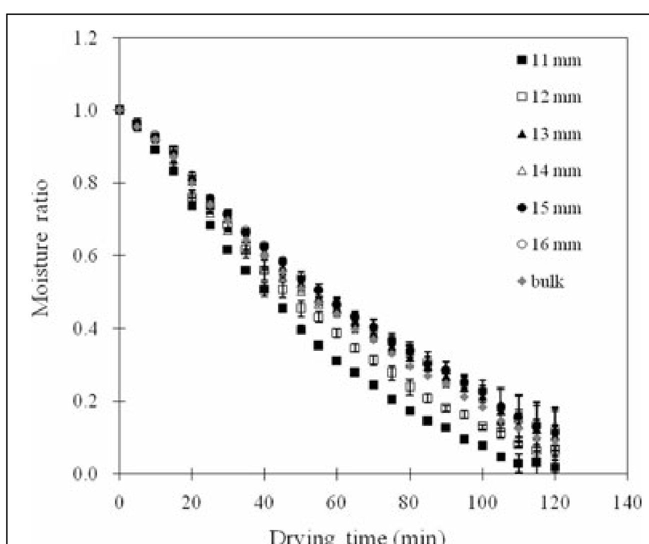

Figure 2 — Effect of berry diameter on the drying curves of blueberries.

description of the CIR system is available in our previous study (Gabel and others 2006).

Drying trials

Three sorted blueberry samples for each group with average diameters of 11, 12, 13, 14, 15, and 16 mm and an unsorted sample (bulk) were dried at 70 °C product temperature.

Under the assumption that the change of coat structure would facilitate water transfer and thus reduce berry breakage by decreasing the vapor pressure, 80 and 90 °C were tested in drying bulk berries with and without NaOH pretreatment. To determine the vapor pressure effect, pretreated and nonpretreated bulk berries were also dried at 70 °C for 50 min to remove most water and reduce the vapor pressure, and then dried at 90 °C until the end.

In all drying tests, the gas flow of the CIR drier was controlled based on the product temperature, measured by a type-T thermocouple inserted underneath the coat of 1 blueberry with diameter of 16 mm to minimize the variation of temperature among berries. In each drying test, 10 to 25 small round sample trays made of metal wire were placed on the large drying tray. Each small tray contained 10 to 15 g of berries with an average loading density of 4.4 kg/m^2. At intervals of 5 to 10 min, 1 small sample tray was removed from the drier for measuring moisture loss. The drying test was stopped at 120 min. The moisture content of the dried products was approximately 30% (wet basis). All the experiments were replicated 3 times at each temperature and the average weight reductions and *MC* were reported.

Determination of drying rate and moisture diffusivity

The moisture ratio (*MR*) of samples was calculated by the equation

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_e is the equilibrium moisture content of the samples (dry basis). Because the value of M_e is relatively small compared to M_t *or* M_0 for IR drying (Diamante and Munro 1993), M_e was assumed to be 0 in this study, based on our experience.

Effective moisture diffusivity for spherical blueberries was calculated using Crank's equation (1975), with these assumptions (Dimatteo and others 2000; El-Beltagy and others 2007): (1) mass transfer is symmetric with respect to the center, (2) blueberries have uniform initial moisture content, (3) main resistance to mass transfer is due to the internal moisture movement, (4) product shrinkage during drying is negligible, and (5) mass transfer is by diffusion only.

Then the equation can be expressed as:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}e^{\left(\frac{-n^2\pi^2 D_e t}{r^2}\right)} \tag{2}$$

where D_e is effective moisture diffusivity (m^2/s), r is radius of the blueberries (m), and t is time (s). For long drying times, Eq. (2) can be simplified to the form

$$\ln(MR) = \ln\frac{6}{\pi^2} - \frac{\pi^2 D_e t}{r^2} \tag{3}$$

Then the effective moisture diffusivity D_e can be calculated by using equation

$$D_e = \frac{-0.101\ln(MR) - 0.0504}{(t/r^2)} \tag{4}$$

The effective moisture diffusivity D_e was calculated at each corresponding moisture content and time in this study. The average effective moisture diffusivity $D_{e,avg}$ was calculated from positive D_e obtained using the data of all positive effective moisture diffusivities (Singh and Gupta 2007) as

$$D_{e,avg} = \frac{\sum_1^n D_e}{n} \tag{5}$$

Effect of temperature on diffusivity is described by the Arrhenius relationship (Singh and Gupta 2007), presented as

$$D_{e,avg} = D_0 e^{-\left(\frac{E_a}{R(T+273)}\right)} \tag{6}$$

where T is temperature (°C), R is gas constant with the value of 8.314×10^{-3} kJ/mol/K, D_0 is effective moisture diffusivity at reference temperature (273 K), and E_a is activation energy (kilojoules per mole). The plot of $\ln(D_{e,avg})$ against inverse of absolute drying temperature was used to determine activation energy E_a.

Scanning electron microscopy

Fresh and NaOH pretreated blueberries before and after IR drying (10 min) were observed by Cryo-SEM for coats and by regular SEM for tissue cells. For regular SEM, samples were subjected to fixation before SEM observation. The fixation was done by immersing samples in fixative consisting of 2.5% glutaraldehyde and 2% formaldehyde in 0.1M sodium cacodylate buffer (pH 5) overnight at 4 °C. The samples were cut into smaller pieces and fixed again in fresh fixative overnight at 4 °C. The samples were rinsed in 2 exchanges of 0.1 M sodium cacodylate buffer (pH 5) with 20 min per exchange and dehydrated in a graded series of ethanol (30%, 50%, 70%, 95%, 100% for 3 times) for 30 min per step. A subset of the samples was cryo fractured in liquid nitrogen. The fractured, frozen samples were picked out of the liquid nitrogen with chilled tweezers and placed back into 100% ethanol to thaw. All samples were critical point dried in a Tousimis 815 Autosamdri critical point dryer (Tousimis, Rockville, Md., U.S.A.). The samples were mounted onto aluminum specimen stubs using a mixture of 2-component "extra-time" epoxy (Loctite Brand, Henkle Technologies, Düsseldorf, Germany, available at local hardware stores) and water-based conductive graphite adhesive (Electron Microscopy Sciences, Hatfield, Pa., U.S.A.). The mixture was approximately equal parts hardener, resin, and graphite. After drying overnight in a desiccator, the samples were coated with gold-palladium in a Desk II sputter-coating unit (Denton Vacuum, Moorestown, N.J., U.S.A.) and viewed at 2 kV in a Hitachi S-4700 scanning electron microscope (Hitachi Corp. Berkshire, RG, Japan).

Dynamic vapor sorption (DVS) measurement

Blueberry samples were carefully peeled by hand. The coats were carefully scribed with a knife to remove the adhered pulp. Dynamic Vapor Sorption (DVS) Advantage apparatus (Surface Measurement Systems NA, Allentown, Pa., U.S.A.) was used in the tests. A blueberry coat of approximately 3 mg (8-mm-dia pieces cut using a stopper borer) was weighed in a stainless steel mesh basket in the DVS equipment. The DVS was programmed to go through a sorption and desorption cycle at 5 equilibrium steps from 98% to 0% RH at 50 ± 0.1 °C; the ratio of mass and time change (dm/dt) was less than 0.001 during the interval period while stepping up or down the % RH. The coat thickness was measured using a micrometer IP 65 (Mitutoyo Manufacturing, Tokyo, Japan) to the nearest 0.00254 mm at 5 random positions by slowly reducing the micrometer gap until

Table 1 — Average moisture diffusivity ($D_{e,avg}$) of blueberries under different conditions ($\times$ 10^{-10} m^2/s)

Blueberries with different diameters (70 °C)						
11 mm	12 mm	13 mm	14 mm	15 mm	16 mm	bulk
8.15 ± 0.95[a]	7.22 ± 0.87[ab]	5.75 ± 0.24[ab]	6.32 ± 0.97[ab]	7.32 ± 0.84[ab]	7.94 ± 1.10[a]	5.33 ± 0.23[b]

Bulk blueberries under different treatments					
Untreated (comb)	Treated (comb)	Untreated (80 °C)	Treated (80 °C)	Untreated (90 °C)	Treated (90 °C)
5.12 ± 0.30[c]	5.33 ± 0.52[c]	6.33 ± 0.67[c]	6.79 ± 0.77[bc]	8.73 ± 1.35[ab]	9.56 ± 1.06[a]

Mean values followed by different letters in a same row are significantly different at $P < 0.05$ level.

the 1st indication of contact. The diffusion coefficients were calculated using the DVS Advanced Analysis Suite v4.3 software (Surface Measurement Systems NA)for DVS Diffusion Analysis of thin film diffusion coefficient for double-sided experiments, which is equivalent to a disk where diffusion takes place on both sides. Triplicate samples were used for each of the 3 blueberry coat treatments. The DVS Standard Analysis Suite v4.3 software for DVS Isotherm Analysis was also used to estimate the sorption and desorption curves and hysteresis of the 3 blueberry coat treatments.

Results and Discussion

Effect of berry size

In the amount of bulk berries, about 45% had diameter of 13 mm and more than 85% had diameters from 11.5 to 14.5 mm (Figure 1). As expected, drying rates increased with decrease in berry size when the diameters decreased from 13 to 11 mm (Figure 2). However, berries with diameters in the range from 13 to 16 mm had very similar drying rates. When a batch of berries with different sizes was dried together, they showed similar drying behavior to those with diameters ranging from 13 to 15 mm. MacGregor (2005) also reported small wild berries had a higher drying rate than large ones. We observed that small blueberries (11 mm) could be heated up more quickly and reached higher peak temperature than large ones when heating was controlled according to the product temperature of 16 mm ones in this study. Therefore, compared to the large ones, small blueberries were exposed to a higher temperature for longer period, especially in later drying stage. This might be the reason that small fruits showed high drying rates.

Even though the average effective moisture diffusivities ($D_{e,avg}$) showed a trend of increase from 5.75×10^{-10} to 7.94×10^{-10} m^2/s when the diameter of the berries increased from 13 to 16 mm, they were not statistically different for berries with diameters of 13, 14, and 15 mm (Table 1). MacGregor (2005) reported that larger blueberries had higher moisture diffusivity, but did not give a reason for this result. We thought it might be due to the fact that large blueberries contain more water but have less specific surface area than small ones, resulting in high vapor pressure. The high vapor pressure would facilitate the water loss from blueberries to the environment and thus result in high effective moisture diffusivity. However, this does not explain why blueberries with diameter of 11 mm showed much higher $D_{e,avg}$ value (8.15×10^{-10} m^2/s) than others. The nonlinear trend in diffusivity values for different diameters (minimum at 13 mm and increasing values toward lower and higher diameters) might be caused by the combination effect of vapor pressure and volume of fruit on the rate of water transfer from the fruit to the environment. The intrinsic reason needs to be further studied. The average effective moisture diffusivity of bulk blueberries (with weight average diameter of 13 mm) was 5.33×10^{-10} m^2/s, being close to the $D_{e,avg}$ value of berries of 13-mm dia, the largest group in the bulk berries.

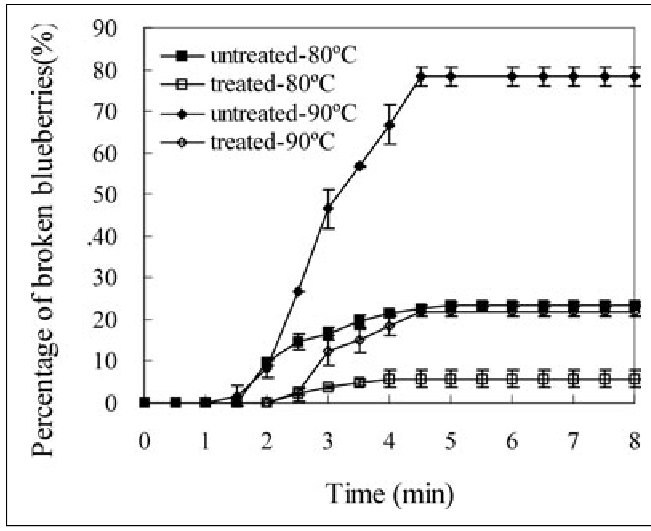

Figure 3 — Effect of NaOH pretreatment on the proportion of broken blueberries during the IR drying process.

Effect of NaOH pretreatment

A batch of blueberries was treated in bulk for the NaOH pretreatment tests. Blueberries without NaOH pretreatment tended to break during drying when temperatures were kept at levels higher than 75 °C for more than 5 min. Compared to smaller berries, bigger ones broke earlier and more easily. NaOH pretreatment reduced the number of broken berries at temperatures higher than 80 °C (Figure 3). The percentage of broken berries was reduced from more than 78% to less than 25% at 90 °C and from 22% to less than 6% at 80 °C when NaOH pretreatment was used. NaOH pretreatment increased drying rates at temperatures higher than 80 °C (Figure 4) as expected. Similar results have been reported on using hot lye solution to pretreat wild blueberries, grapes, and plums by convectional air-drying at temperatures lower than 70 °C (Azzouz and others 2002; Doymaz 2006; Sacilika and others 2006). However, when berries were dried at 70 °C for 50 min before temperature increased to 90 °C (labeled as comb in the figure), the drying rate was not affected by NaOH pretreatment. This might be because the vapor pressure was reduced enough during the lower temperature (70 °C) drying stage. Clearly, then, the pretreatment is very important for reducing broken berries and increasing the drying rate when high drying temperatures are used.

We have observed that sodium hydroxide solution dipping treatment made the product bluer after IR drying compared to nontreated samples, which is desirable. This is different from sugar-infused blueberries without dipping pretreatment, which were redder, lighter, and softer after IR drying (Shi and others 2008).

Table 1 shows that high temperature had high diffusivities. NaOH pretreatment resulted in slightly higher effective moisture diffusivity even though the change was not statistically significant. This is consistent with previous results found in drying of grapes and plums (Doymaz 2006; Sacilika and others 2006). In this study, the average effective moisture diffusivity increased from 6.33 × 10^{-10} to 8.73 × 10^{-10} m^2/s when drying temperature increased from 80 to 90 °C for bulk blueberries not subjected to NaOH pretreatment, and up to 6.78 × 10^{-10} and 9.56 × 10^{-10} m^2/s for blueberries subjected to such pretreatment. The highest moisture diffusivity of grapes treated with 1% NaOH solution previously reported was 4 to 8 × 10^{-11} m^2/s at 70 °C with air drying, which is much lower than that in this study (Azzouz and others 2002).

Microstructure of blueberries

To determine the intrinsic reason for the effect of NaOH pretreatment on the drying characteristics of blueberries, we studied the microstructure of the berries under different treatment by SEM. After the NaOH treatment, the wax layer of berries was partially removed (Figure 5A and 5B), which was compared to the sample without pretreatment. It has been reported that NaOH treatment could scald the coat of fruits, causing fissures that enable water to cross the initially impermeable membrane (Riva and Peri 1983). Compared with the untreated blueberries, the pretreated berries had fewer obvious cracks on the surface and slight deformation on the structure of some tissue cells under the epidermis after the drying process (Figure 5A-10 and 5B-10). The plasma membrane of the epidermal cells and some of the inner cells might also be disrupted by the pretreatment, since no clear intact plasma membrane like that in untreated blueberries was found in the cells of pretreated samples (Figure 5A-I and 5B-I). With these changes of the microstructure of pretreated blueberries, the increasing high vapor pressure inside fruits could be released or reduced and thus the number of broken blueberries was reduced.

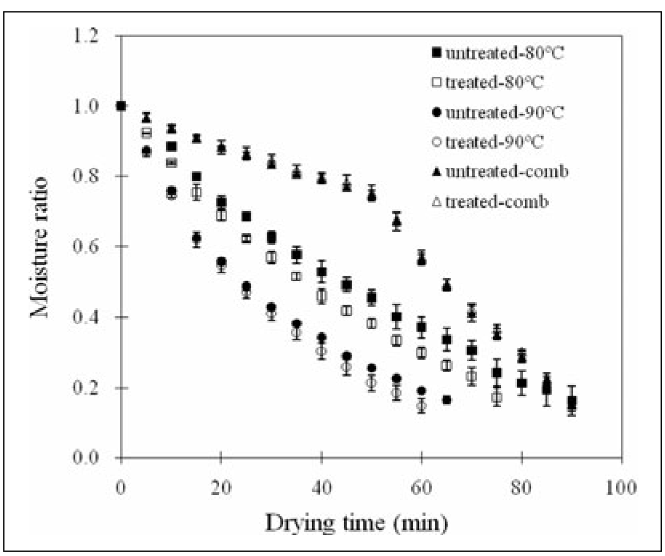

Figure 4—Effect of NaOH pretreatment on the drying curves of blueberries.

Diffusion coefficient of blueberries

To understand the effect of NaOH pretreatment on the drying properties of blueberries, diffusion properties of the berry coats were measured using the DVS method. The results are shown in Table 2. The moisture diffusion coefficient of the coats showed a trend of increase when NaOH treatment was used. However, when the statistical analysis was performed on data, the significance levels of most of data were low. During the courses of sorption and desorption, the moisture diffusion coefficient of pretreated blueberry coats was higher than that of untreated ones. Such differences showed more significantly for lower relative humidity levels, from 0% to 48%, than for higher levels. It indicated that NaOH pretreatment made the blueberry coats easier for water to pass through and redistribute. Thus lower water and vapor pressure, the main reasons for blueberry break, accumulated under the berry coats during the IR heating. Therefore, the number of broken blueberries was reduced and the drying rate increased during the drying process, especially when moisture content of the samples was lower than 48%.

When environmental relative humidity was in the range of 48% to 72%, the blueberry coats had higher moisture diffusion coefficient than at other relative humidity levels, for both pretreated and nonpretreated berries (Table 2). This might explain the less effect of NaOH pretreatment when variable temperature drying was used. When blueberries were dried at 70 °C for 50 min, the moisture content decreased to the levels giving higher moisture diffusion coefficient, resulting in high less vapor pressure under berry coat and higher drying rate in later stages when temperature increased to 90 °C. Therefore, the NaOH pretreatment had very limited effect on the drying rate and breakage of blueberries under the tested variable drying conditions.

Conclusions

Blueberry size significantly affects drying rate and moisture diffusivity. To obtain high-quality products with similar moisture content, berries that are too small and too large may be removed before drying. Pretreatment with hot NaOH solution increased the drying rate and moisture diffusivity, and significantly reduced the numbers of broken berries, especially at high drying temperatures. The intrinsic reason for the effect of NaOH pretreatment on the drying characteristics of blueberries was the changes in the surface and cell microstructure of blueberries.

Table 2—Average of diffusion coefficient for blueberries coats (×10^{-8} cm^2/s).

Desorption			Adsorption		
Previous RH%–Target RH%	Untreated	NaOH treated	Previous RH%–target RH%	Untreated	NaOH treated
96-72	5.16 ± 3.22	9.86 ± 9.10[c]	0-24	2.04 ± 0.75	4.21 ± 2.93[b]
72-48	14.01 ± 6.82	19.44 ± 12.52[c]	24-48	7.67 ± 2.75	16.88 ± 11.66[a]
48-24	7.44 ± 3.03	14.04 ± 8.67[b]	48-72	11.51 ± 4.40	18.17 ± 12.19[c]
24-0	0.910 ± 0.37	1.61 ± 1.21[b]	72-96	2.03 ± 1.09	3.85 ± 3.55[c]

[a], [b], and [c] indicate significant difference at $P < 0.05$, $P < 0.1$, and $P < 0.1$, respectively, compared to the untreated sample.

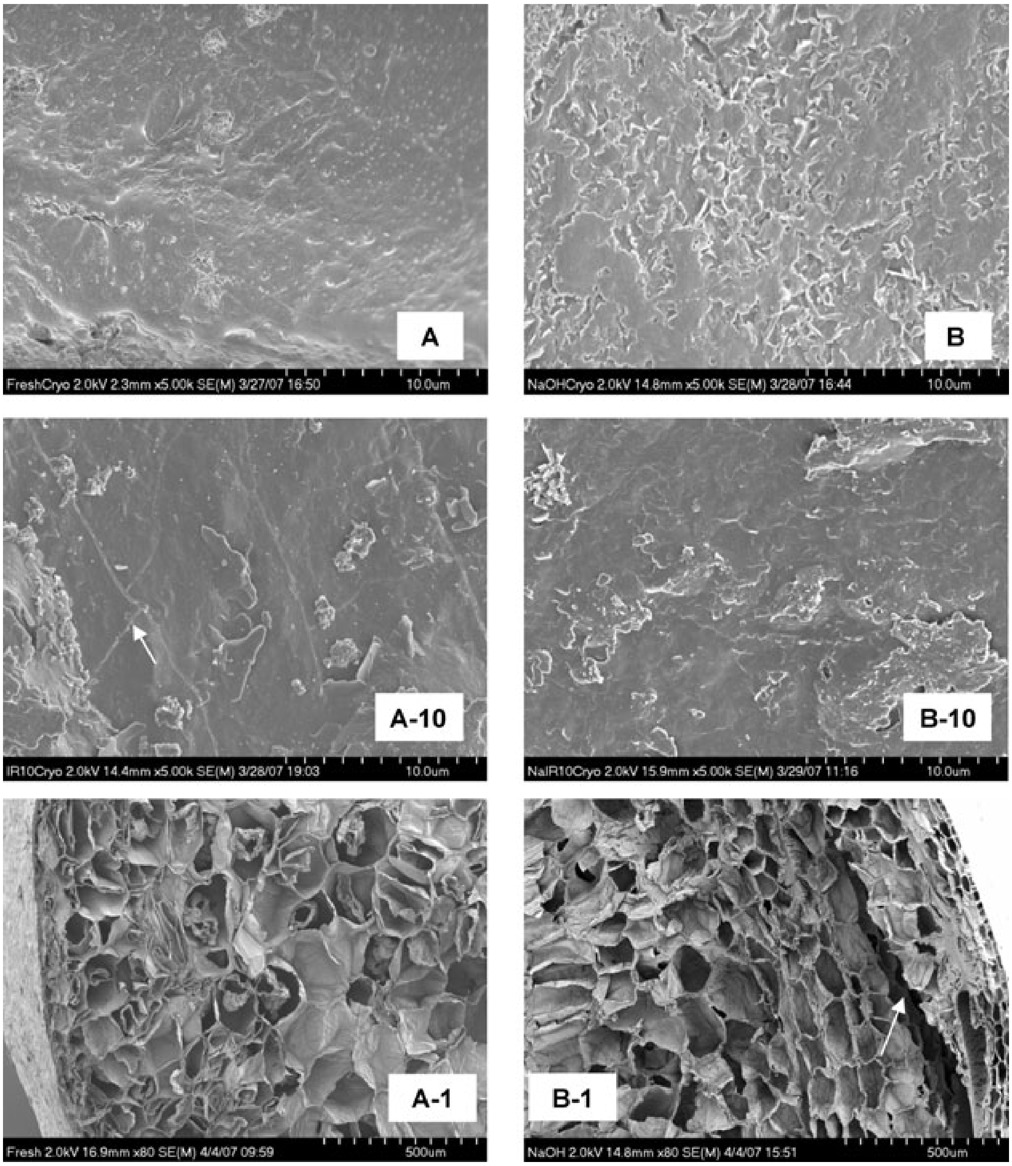

Figure 5—The microstructure of blueberries with and without NaOH pretreatment. Cryo-SEM of the coat of blueberries without NaOH pretreatment before (A) and after IR drying for 10 min (A-10); Cryo-SEM of the coat of blueberries with NaOH pretreatment before (B) and after IR drying for 10 min (B-10); regular SEM for the cross section of blueberries with (A-I) and without (B-I) NaOH pretreatment. The magnification is 5 *k* for A, A-10, B, and B-10 and 80 for A-I and B-I.

Acknowledgments

The authors thank Don Olson, Western Regional Research Center, USDA-ARS, for his support in the experiments and partial financial support from Innovative Foods Inc. under the USDA ARS CRADA Nr 58-3K95-5-1089. The research was conducted at the Western Regional Research Center, USDA-ARS, and the Dept. of Biological and Agricultural Engineering, Univ. of California, Davis, Calif.

Nomenclature

CIR catalytic infrared
D_0 effective moisture diffusivity at reference temperature (273 K) (m^2/s)
D_e effective moisture diffusivity (m^2/s)
$D_{e,avg}$ average effective moisture diffusivity (m^2/s)
DVS Dynamic Vapor Sorption
E_a activation energy (kJ/mol)
IR infrared radiation
MC moisture content
M_0 moisture content of blueberries at start time (g/g dry solid)
Me moisture content of blueberries at equilibrium point (g/g dry solid)
MR moisture ratio of blueberries
M_t moisture content of blueberries at time t (g/g dry solid)
r radius of blueberries (m)
R gas constant with the value of 8.314×10^{-3} kJ/mol/K
RH relative humidity
SEM scanning electric microscopy
t drying time (s)
T temperature (°C)

References

Abe T, Afzal TM. 1997. Thin-layer infrared radiation drying of rough rice. J Agric Eng Res 67(4):289–97.
Adonis M, Khan MTE. 2004. Combined convective and infrared drying model for food applications. 2004 IEEE AFRICON: 7th AFRICON Conference in Africa: technology innovation. p 1049–52.
Allan-Wojtas P, Goff HD, Stark R, Carbyn S. 1999. The effect of freezing method and frozen storage conditions on the microstructure of wild blueberries as observed by cold-stage scanning electron microscopy. Scanning 21:334–47.
Azzouz S, Guizani A, Jomaa W, Belghith A. 2002. Moisture diffusivity and drying kinetic equation of convective drying of grapes. J Food Eng 55(4):323–30.
Bolin HR, Petrucci V, Fuller G. 1975. Characteristics of mechanically harvested raisins produced by dehydration and by field drying. J Food Sci 40(5):1036–8.
Chen CR, Ramaswamy HS, Alli I. 2001. Prediction of quality changes during osmo-convective drying of blueberries using neural network models for process optimization. Drying Technol 19(3/4):507–23.

Diamante LM, Munro PA. 1993. Mathematical modeling of the thin layer solar drying of sweet potato slices. Sol Energy 51(4):271–6.
Dimatteo M, Cinquanta L, Galiero G, Crescitelli S. 2000. Effect of a novel physical pretreatment process on drying kinetics of seedless grapes. J Food Eng 46(2): 83–9.
Donahue DW, Bushway AA, Moore KE, Hazen RA. 1999. Forced air removal of surface moisture from Maine wild blueberries for the fresh pack market. Applied Eng Agric 15(2):147–52.
Doymaz I. 2004. Effect of pre-treatments using potassium metabisulphide and alkaline ethyl oleate on the drying kinetics of apricots. Biosystems Eng 89(3):281–7.
Doymaz I. 2006. Drying kinetics of black grapes treated with different solutions. J Food Eng 76(2):212–7.
Doymaz I, Pala M. 2002. Hot-air drying characteristics of red pepper. J Food Eng 55(4):331–5.
El-Beltagy A, Gamea GR, Amer Essa AH. 2007. Solar drying characteristics of strawberry. J Food Eng 78(2):456–64.
Gabel MM, Pan ZL, Amaratunga KSP, Harris LJ, Thompson JF. 2006. Catalytic infrared dehydration of onions. J Food Sci 71(9):E351–7.
George SD, Cenkowski US, Muir WE. 2004. A review of drying technologies for the preservation of nutritional compounds in waxy skinned fruit. In 2004 North Central ASAE/CSAE Conference, Manitoba, Canada, September 24 to 25, 2004.
Hashimoto AMU, Kameoka T. 1999. Effect of infrared irradiation on drying characteristics of wet porous materials. Drying Technol 17(7 to 8):1613–26.
Kim SJ, Lee KJ, Kim SI. 2003. Water sorption of poly(propylene glycol)/poly(acrylic acid) interpenetrating polymer network hydrogels. React Func Polym 55(1): 69–73.
Kumar A, Tiwari GN. 2006. Effect of shape and size on convective mass transfer coefficient during greenhouse drying (GHD) of jaggery. J Food Eng 73(2):121–34.
LaTonya KL, Thomas GP. 2006. Use of the dynamic vapor sorption meter to measure skin hydration properties, *in vitro*. Skin Res Technol 12(1):36–42.
Lin Y, Lee T, King A. 2004. Quality of sweet potato dehydrated by far-infrared freeze-drying. J Agric Forest 53(2):109–19.
Lin YP, Lee TY, Tsen JH, King VAE. 2007. Dehydration of yam slices using FIR-assisted freeze drying. J Food Eng 79(4):1295–301.
MacGregor W. 2005. Effects of air velocity, air temperature, and berry diameter on wild blueberry drying. Drying Technol 23(1/2):387–96.
Mowry JK, Heldman DR. 1974. Analysis of moisture removal from the surface of blueberry fruit using air flow. Trans ASAE 17(2):360–3.
Paakkonen K, Havento J, Galambosi B, Pyykkonen M. 1999. Infrared drying of herbs. Agric Food Sci Finland 8(1):19–27.
Ramaswamy HS, Nsonzi F. 1998. Convective-air drying kinetics of osmotically pretreated blueberries. Drying Technol 16(3-5):743–59.
Raouzeos GS, Saravacos GD. 1986. Solar drying of raisins. Drying Technol 4(4):633–49.
Riva M, Peri C. 1983. Etude du sechage des raisins. Effect de traitements de modification de la surface sur la cinetique du sechage. Sciences des Alisments 3: 527–50.
Riva M, Peri C. 1986. Kinetics of sun and air drying of different varieties of seedless grapes. Int J Food Sci Technol 21(5):199–208.
Rohrbach RP. 1977. Air jet drying and dewatering of blueberries. Trans ASAE 20(5):992–5.
Sacilika K, Elicina AK, Unalb G. 2006. Drying kinetics of Üryani plum in a convective hot-air dryer. J Food Eng 76(3):362–8.
Sapers GM, Burgher AM, Philips JG, Jones SB, Stone EG. 1984. Effects of freezing, thawing and cooking on the appearance of highbush blueberries. J Amer Soc Hort Sci 109(1):112–7.
Sharma GP, Verma RC, Pathare P. 2005. Mathematical modeling of infrared radiation thin layer drying of onion slices. J Food Eng 71(3):282–6.
Shi J, Pan Z, McHugh TH, Wood D, Hirschberg E, Olson D. 2008. Drying and quality characteristics of fresh and sugar-infused blueberries dried with infrared radiation heating. Lebensm Wiss Technol. Forthcoming.
Singh B, Gupta AK. 2007. Mass transfer kinetics and determination of effective diffusivity during convective dehydration of pre-osmosed carrot cubes. J Food Eng 79(2):459–70.
Venkatachalapathy K, Raghavan GSV. 1998. Microwave drying of osmotically dehydrated blueberries. J Microw Power Electro Energy 33(2):95–102.
Wang J, Sheng K. 2006. Far-infrared and microwave drying of peach. Lebensm Wiss Technol 39(3):247–55.